



Advanced Environmental Barrier Coating Development for SiC-SiC Ceramic Matrix Composite Components

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Durable Environmental Barrier Coating Systems for Ceramic Matrix Composites (CMCs):

Enabling Technology for Next Generation Low Emission, High Efficiency and Light-Weight Propulsion

— NASA Environmental barrier coatings (EBCs) development objectives

- Help achieve future engine temperature and performance goals
- Ensure system durability – towards prime reliant coatings
- Establish database, design tools and coating lifing methodologies
- Improve technology readiness



Fixed Wing Subsonic Aircraft



Supersonics Aircraft



Hybrid Electric Propulsion Aircraft

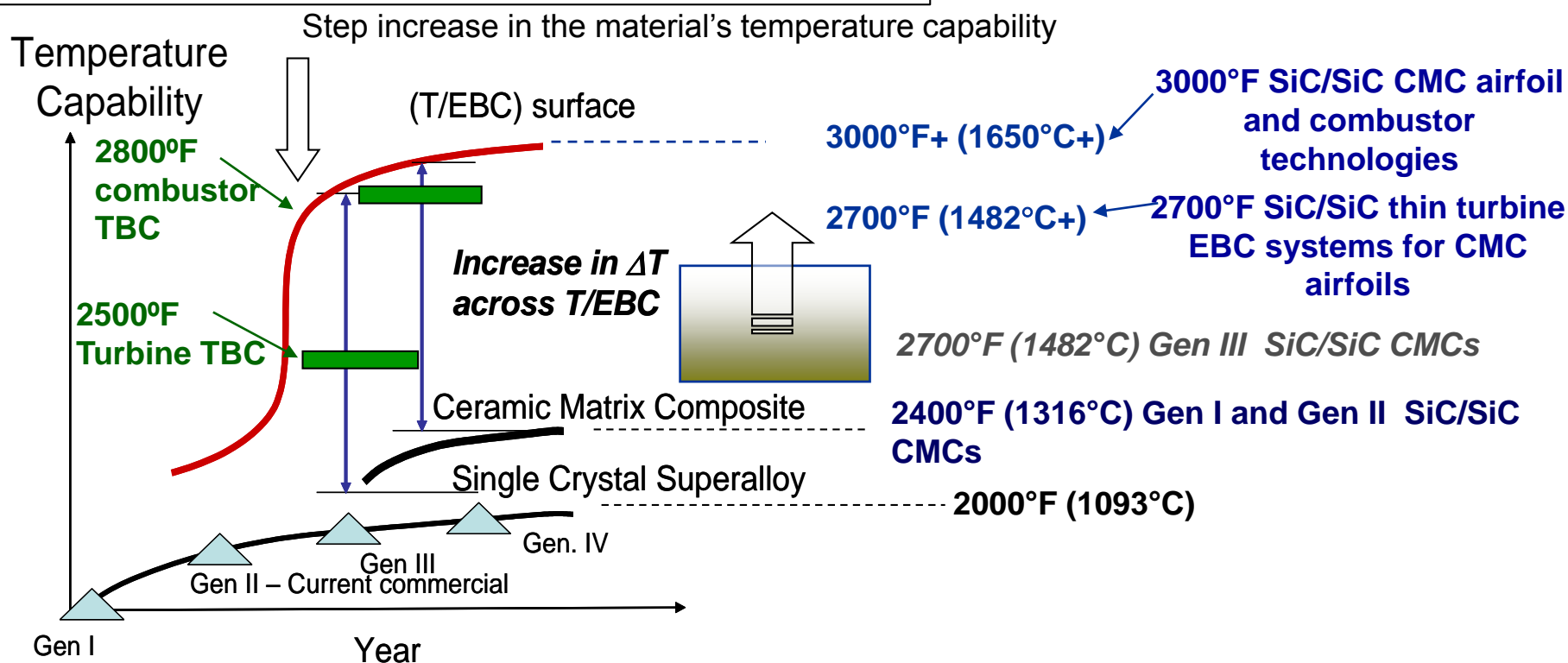
NASA Environmental Barrier Coating Development Goals

Emphasize temperature capability, performance and durability

- 2700-3000°F (1482-1650°C) turbine and CMC combustor coatings
- 2700°F (1482°C) EBC bond coat technology for supporting next generation engines
- Develop innovative coating technologies and life prediction approaches
 - Meet 1000 h for subsonic aircraft and 9,000 h for supersonics/high speed aircraft hot-time life requirements

* **Recession: <5 mg/cm² per 1000 hr (40-50 atm., Mach 1~2)**

** **Component strength and toughness requirements**





Outline

- **Advanced EBC systems development for CMC airfoils and combustors**
 - Prime-reliant EBCs for CMCs: a turbine engine design requirement
 - Fundamental recession of SiC/SiC
 - Thermomechanical, environment and thermochemical stability design considerations
 - Advanced EBC processing, testing and durability
 - NASA 2700-3000°F (1482-1650°C) EBC material systems
 - Current turbine and combustor EBC coating emphases – coating configurations
- **Environmental barrier coating system development**
 - NASA 2700°F EBC technologies
- **Design tool and life prediction perspectives of EBC coated CMC components**
- **Summary and future directions**

Fundamental Recession Issues of CMCs and EBCs

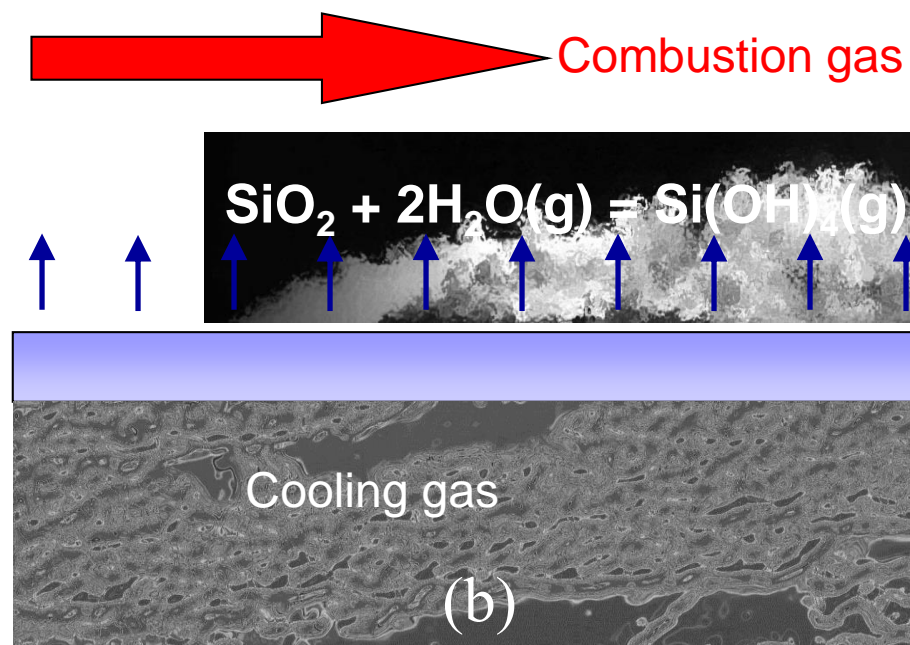
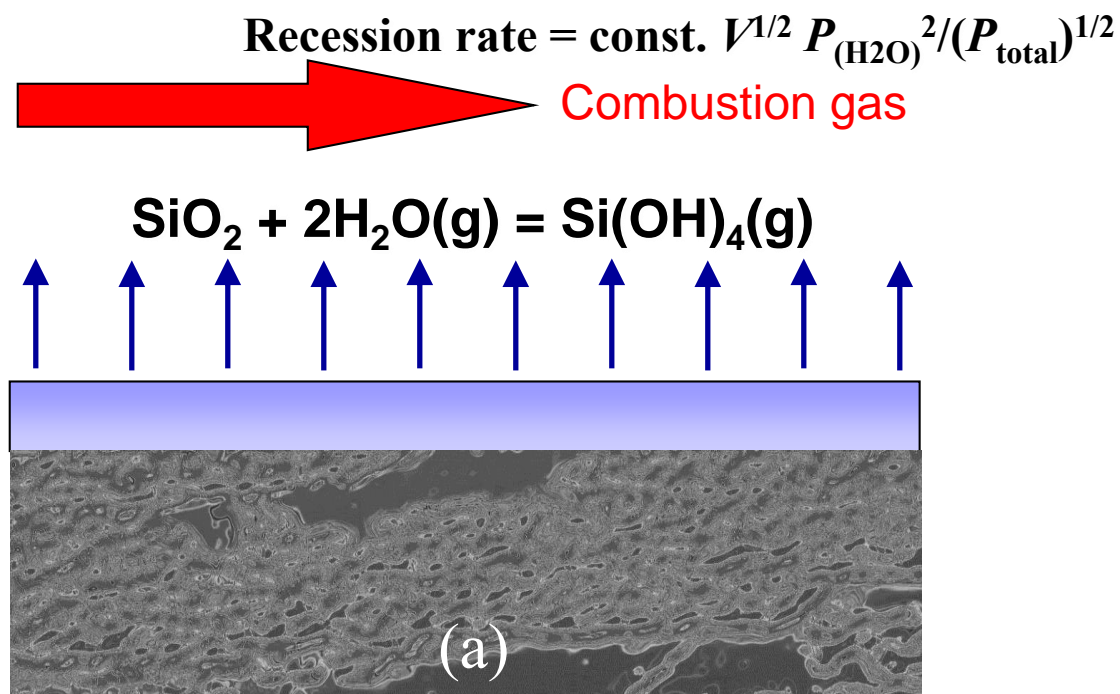
- **Recession of Si-based Ceramics**

(a) Convective; (b) Convective with film-cooling

- High temperature Capable and Low SiO_2 activity EBC system development

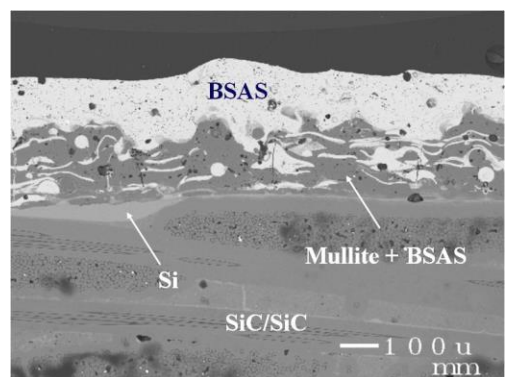
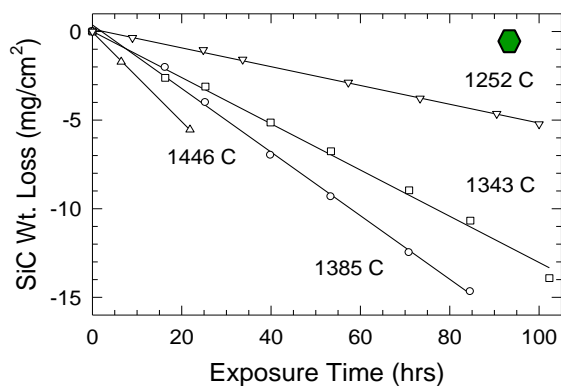
- **Advanced rig testing and modeling**

More complex recession behavior of CMC and EBCs in test rigs simulated combustion flow and pressure conditions

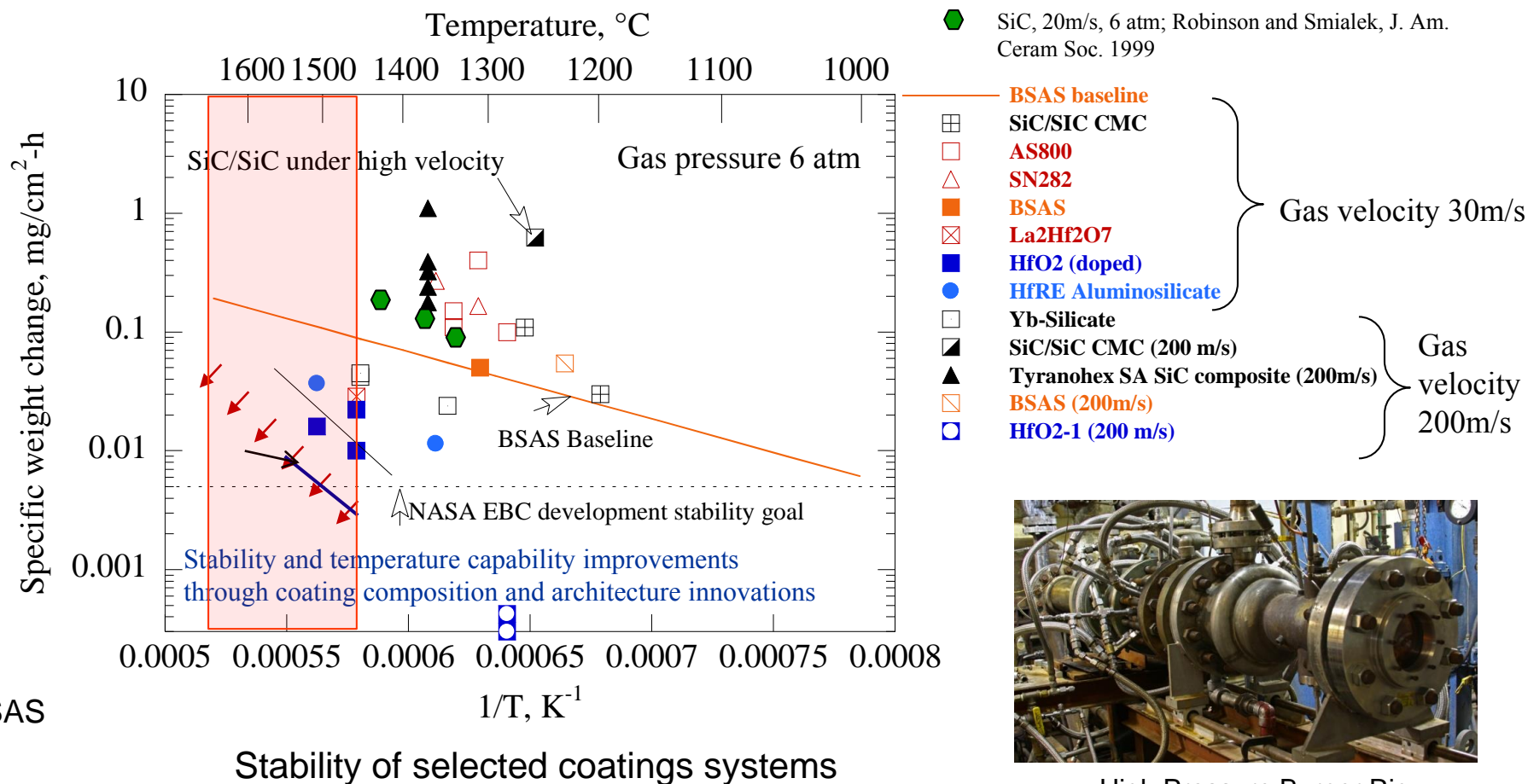


Environmental Stability of Selected Environmental Barrier Coatings Demonstrated in NASA High Pressure Burner Rig

- EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environments
- Focused on 2700-3000°F EBCs
- More stable turbine coatings developed under NASA programs for advanced engine applications



First generation EBC: CMC/Si/Mullite/BSAS



High Pressure Burner Rig



Advanced EBC Developments

- Fundamental studies of environmental barrier coating materials and coating systems, stability, temperature limits and failure mechanisms
- Focus on high performance, high stability HfO_2 - and $\text{ZrO}_2\text{-RE}_2\text{O}_3\text{-SiO}_2/\text{RE}_2\text{Si}_{2-x}\text{O}_{7-2x}$ environmental barrier systems
 - More advanced, multicomponent composition and composite EBC systems to improve the temperature capability, strength and toughness
 - Develop $\text{HfO}_2\text{-Si}$ based + X (dopants) bond coat systems for 2700°F (1482°C) long-term applications
 - Develop *prime-reliant* $2700^\circ\text{F}+$ (1482°C) Rare Earth (RE)-Si + X (dopants) bond coat systems for advanced integrated EBC-CMC systems, improving bond coat temperature capability and durability
- Processing optimizations for improved composition control and process robustness



Advanced EBC Developments – Development Timelines

— Major development milestones:

- 1995-2000: BSAS/Mullite+BSAS/Si
- 2000-2004: $\text{RE}_2\text{Si}_2\text{O}_7$ or RE_2SiO_5 /BSAS+Mullite/Si
- 2000-2004 - 3000°F EBC systems:

Low conductivity (HfO_2 - RE_2O_3 -X Dopants) EBCs / $\text{RE}_2\text{Si}_2\text{O}_7$ or RE_2SiO_5 and/or BSAS+Mullite/Si and Oxide + Si bond coats;

- HfO_2 -Si based bond coats developed to overcome low melting point Si bond coat issues
- Along with ceramic component demonstrations in rigs

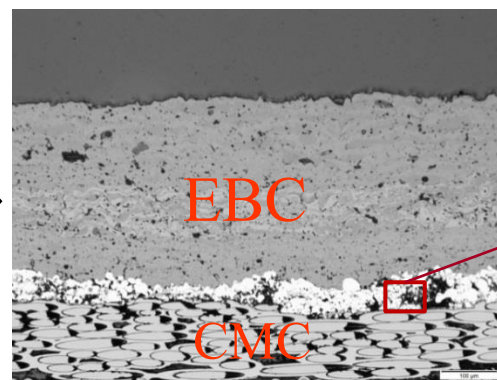
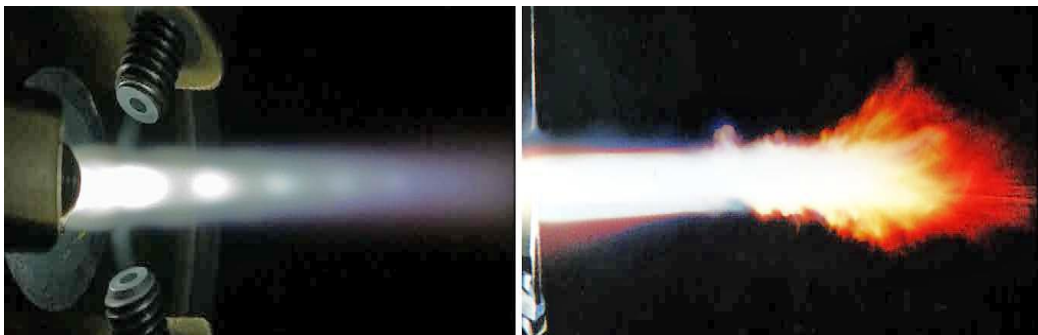
- 2005-2011 - Turbine coating systems:

Multi-component, HfO_2 -Rare Earth Oxide- SiO_2 / multi-component Rare Earth Silicate/ HfO_2 -Si systems

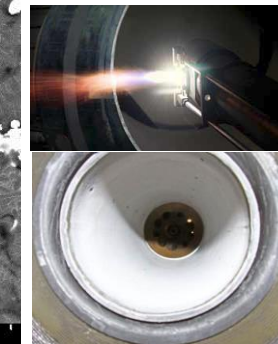
- RE- HfO_2 -X/Multicomponent RE-silicate / HfO_2 -Si +X (doped)

- 2009 - present: Improved EBC compositions and processing; advanced 2700F RE-Si bond coats
 - e.g., (Gd,Yb,Y)Si bond coats and top coats

EBC Processing using Plasma Spray and EB-PVD

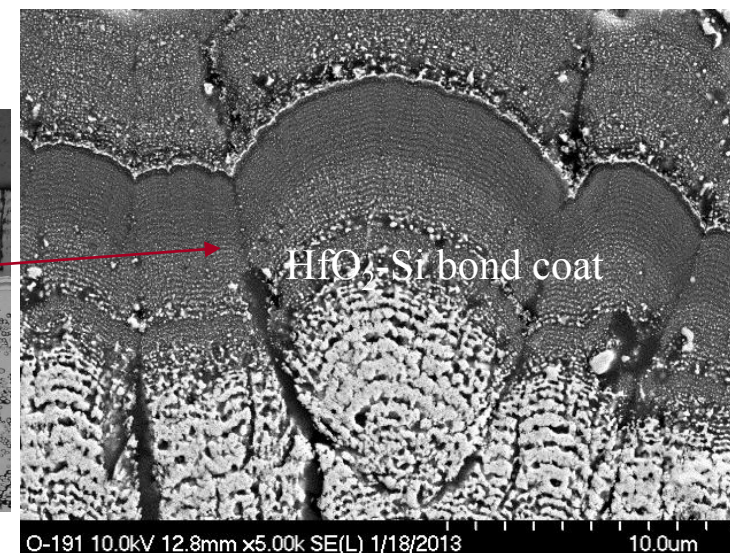
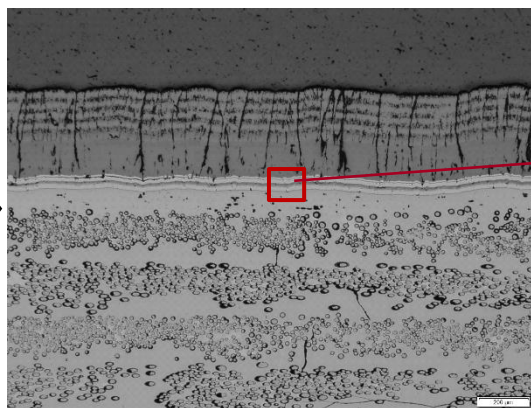
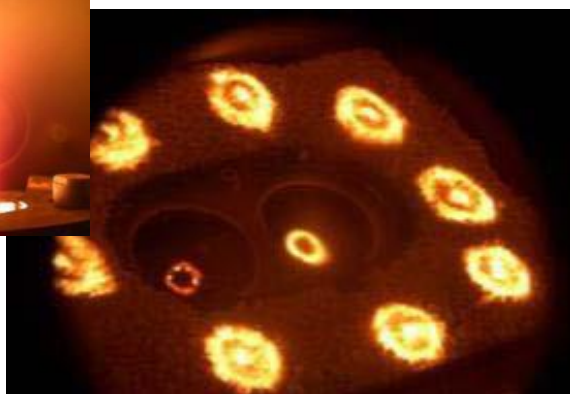


HfO₂-Si bond coat

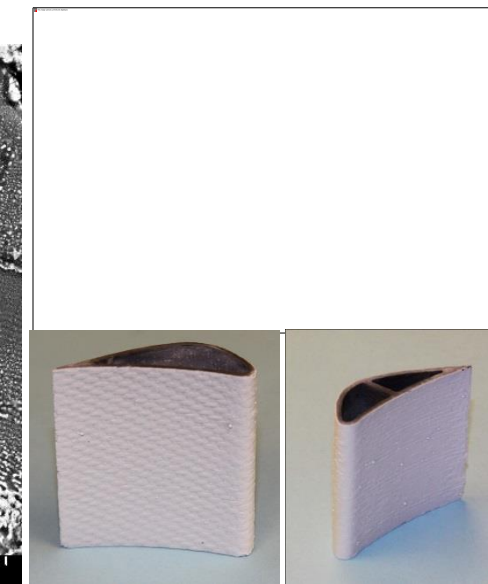


EBC Coated SiC/SiC
CMC Inner and Outer
Liner Demo

Triplex Pro (Oerlikon Metco) Processing and Advanced NASA
EBCs – combustor liner demos



HfO₂-Si bond coat

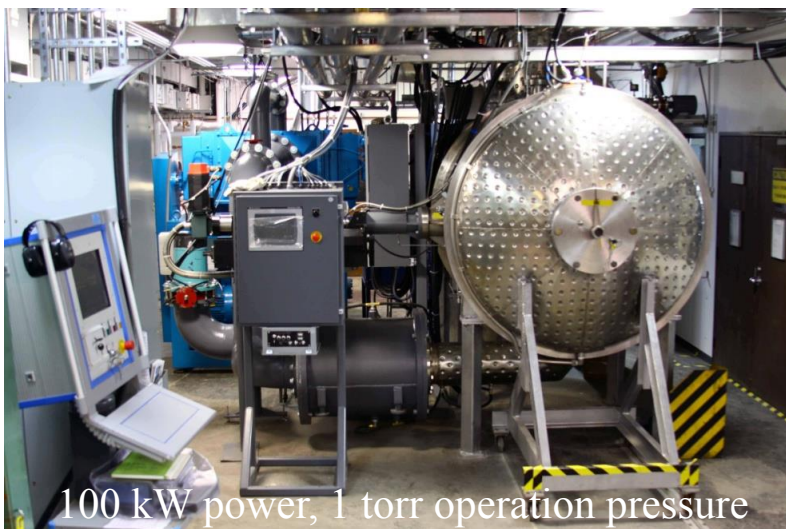
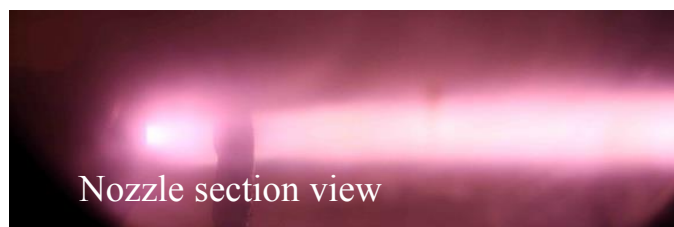


EBC coated SiC/SiC
CMC Vane Airfoils Demo

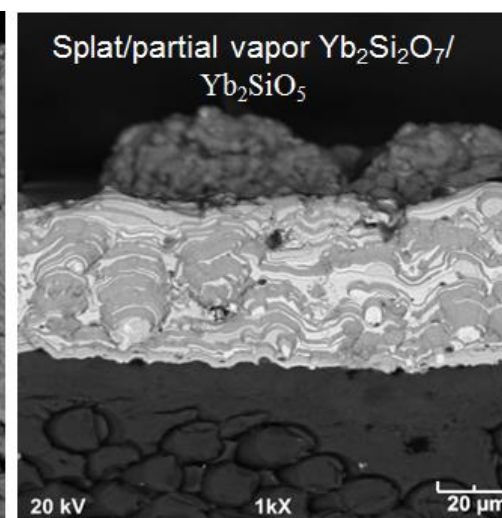
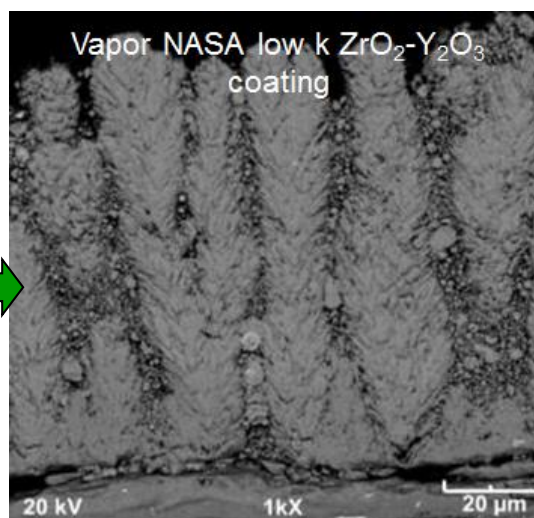
Directed Vapor EB-PVD Processed Advanced EBCs – Turbine Vane Airfoil Demos

Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

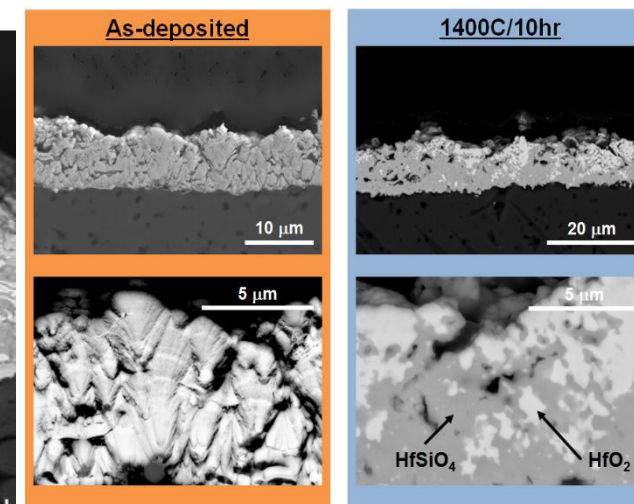
- NASA PS-PVD and PS-TF coating processing using Sulzer (Oerlikon) newly developed technology
 - High flexibility coating processing – PVD - splat coating processing at lo pressure (at ~1 torr)
 - High velocity vapor, non line-of-sight coating processing potentially suitable for complex-shape components
 - Significant progress made in processing the advanced EBC and bond coats



NASA PS-PVD Coater System



Processed coating systems



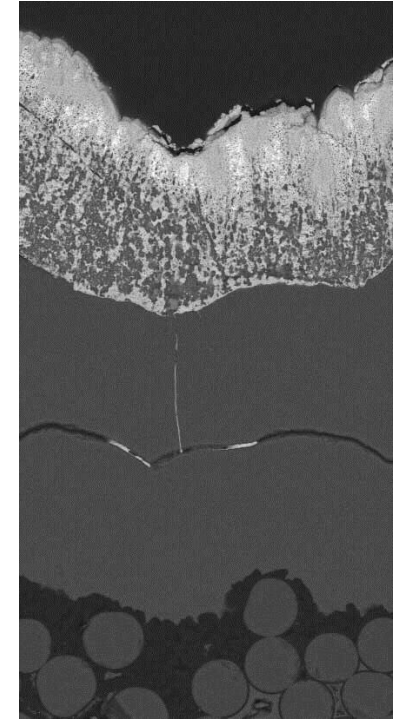
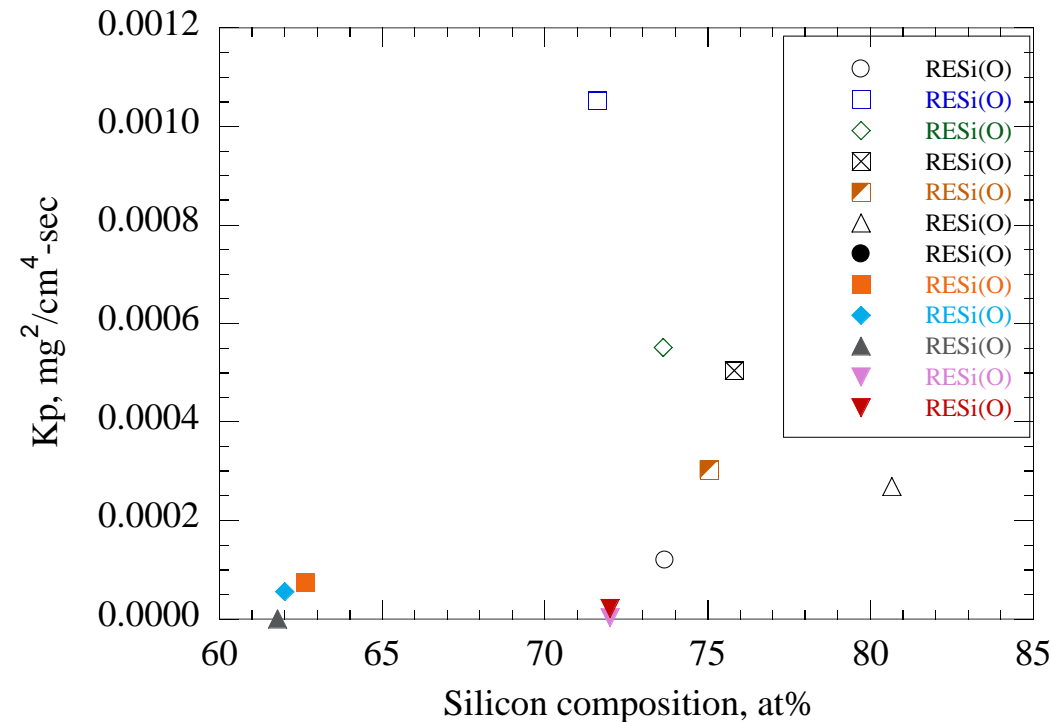
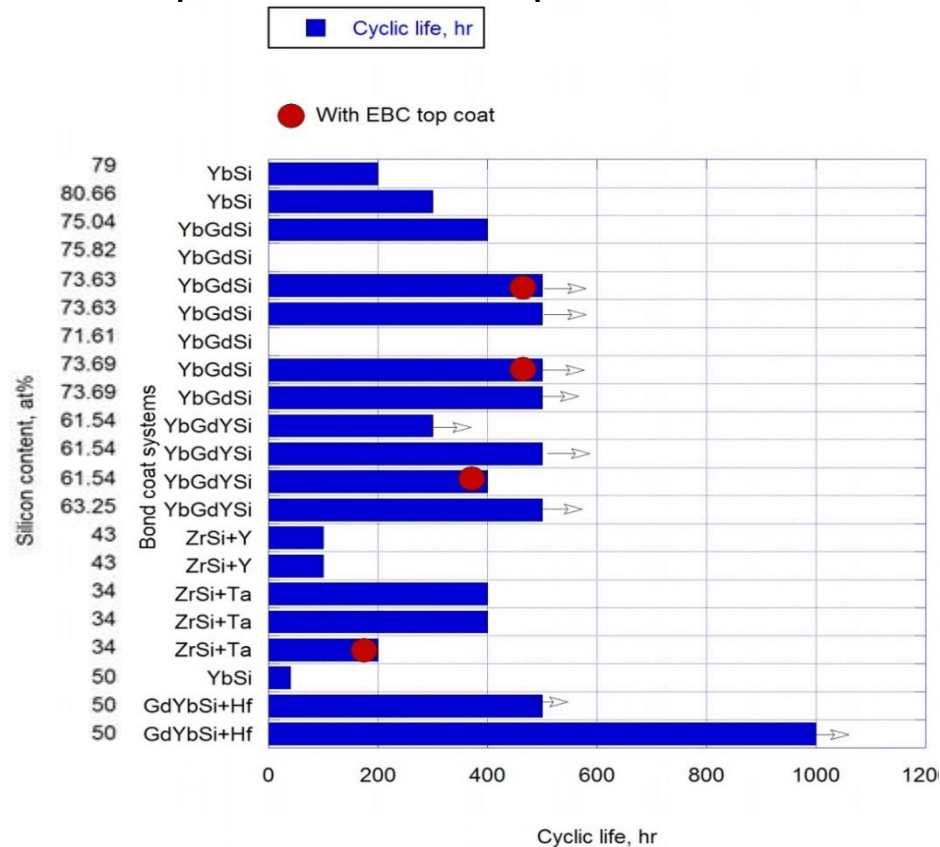
$\text{HfO}_2\text{-Si}$ bond coat

Furnace Cycle and Oxidation Test Results of Selected RESi and ZrSi Based Bond Coats



- Testing in Air at 1500°C, 1 hr cycles

- Multi-component RESiO+X series 2700°F+ EBC bond coat compositions and processing developed
- The 2700°F+ EBC bond coat systems showed promise for furnace cyclic durability and oxidation resistance at 1500°C tests
- Completed initial composition down-selects



An oxidation tested bond coat EBC specimen after 1500°C 100 h testing

Furnace cyclic testing in Air at 1500°C, 1 hr cycles

Oxidation kinetics studied using TGA in flowing O₂

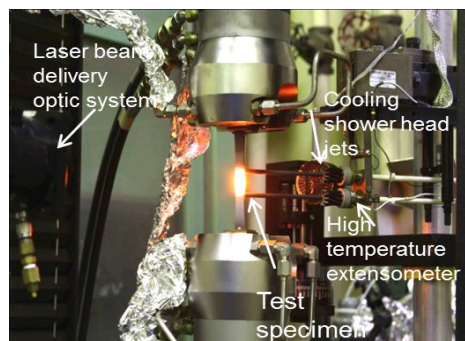
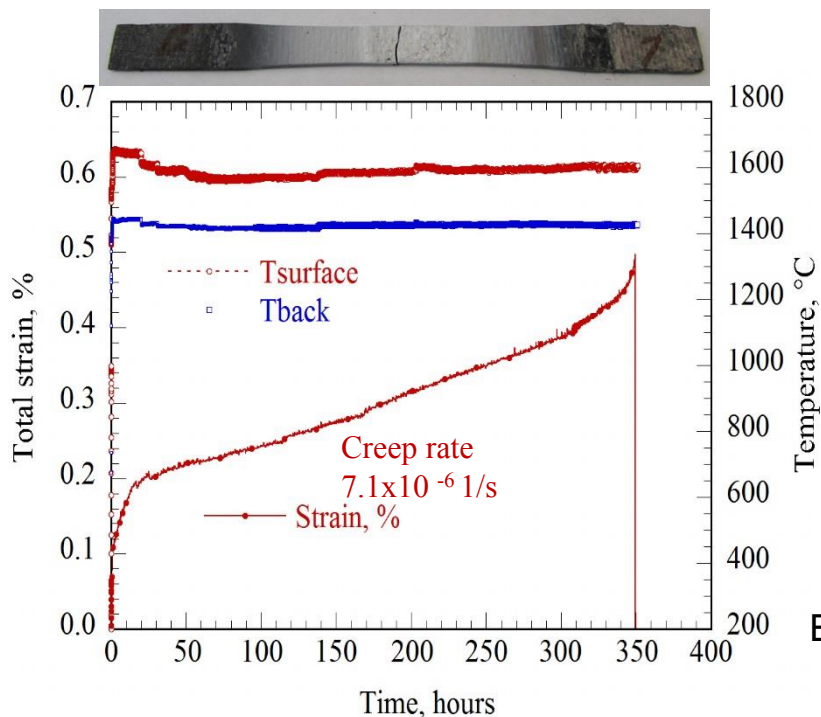
Laser Rig Thermomechanical Creep - Fatigue Tests of Advanced 2700°F+ RESi Bond Coats and EBC Systems

- APS, PVD and EB-PVD processed 2700°F bond coats and EBCs on SiC/SiC CMC: focus on creep, fatigue high heat flux testing at temperatures of 1316-1482°C+ (2400-2700°F+) – Selected Examples

EB-PVD Rare Earth Silicate EBC/YbGdYSi
bond coat on Hyper Therm CVI-MI

$T_{\text{EBC surface}}$ 2850-3000°F (1600-1650°C)

$T_{\text{cmc back}}$ at ~2600°F (1426°C)



Laser rig testing

Creep and Fatigue Tests with CMAS



Air Plasma Sprayed $\text{YSi}+\text{Hf-RESilicate}$
EBC Bond Coat series on CVI-MI SiC/SiC
1400°C, at 10 ksi, 400 hr



EB-PVD $(\text{Hf,Yb,Gd,Yb})_2\text{Si}_{2-x}\text{O}_{7-x}$ EBC/GdYbSi bond
coat on Rolls Royce CVI-MI SiC/SiC (with CMAS)
1537°C, 10ksi, 300 h fatigue (3 Hz, R=0.05)

Fatigue Tested



PVD GdYSi coated on Hyper Them CVI-MI
SiC/SiC
1316°C, 10ksi, 1000 h fatigue (3 Hz, R=0.05)



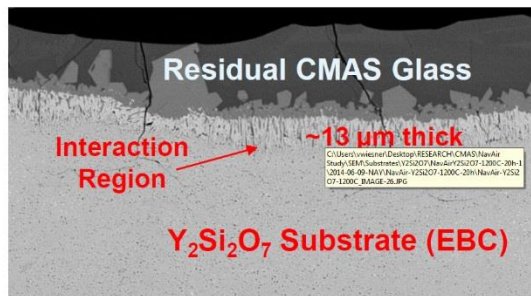
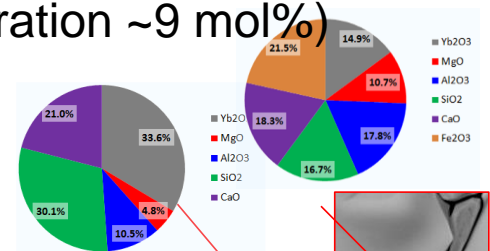
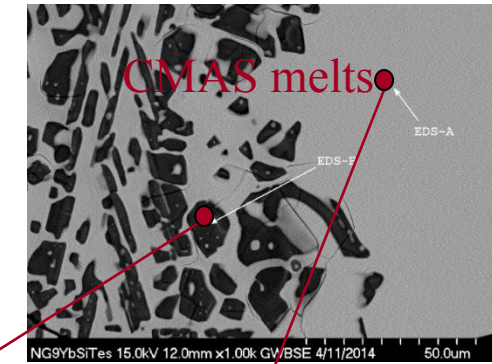
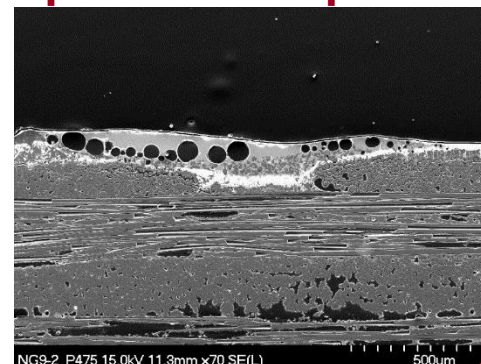
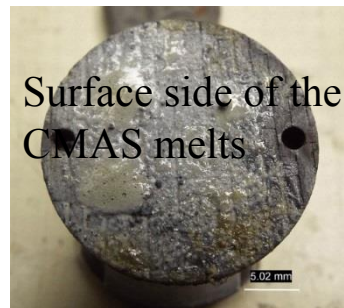
PVD GdYbYSi coated on GE Prepreg SiC/SiC
1316°C, 15ksi, 1169 h fatigue (3 Hz, R=0.05)



NASA 2700°F(1482°C)+ *EBC System 188*
on SA Tyrannohex SiC Composite, 1482°C
15 ksi, 500hr

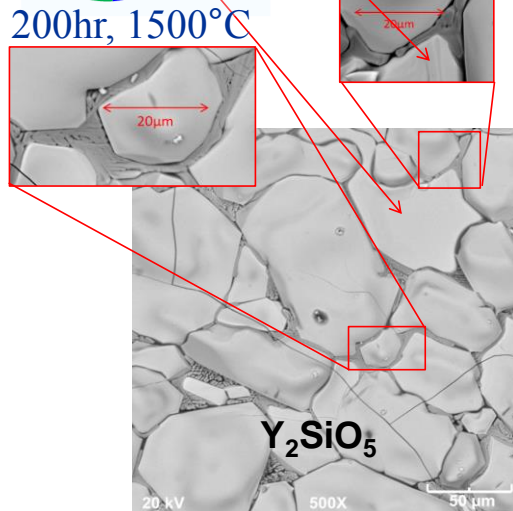
High Stability and CMAS Resistance Demonstrated by Advanced High Melting Point Coating, and Multi-Component Compositions

- Demonstrated Calcium-Magnesium-Alumino-Silicate (CMAS) resistance for NASA RESi system at 1500°C, 100 hr
- Silica-rich phase precipitation
- Still some rare earth elements leaching into the melts (low concentration ~9 mol%)

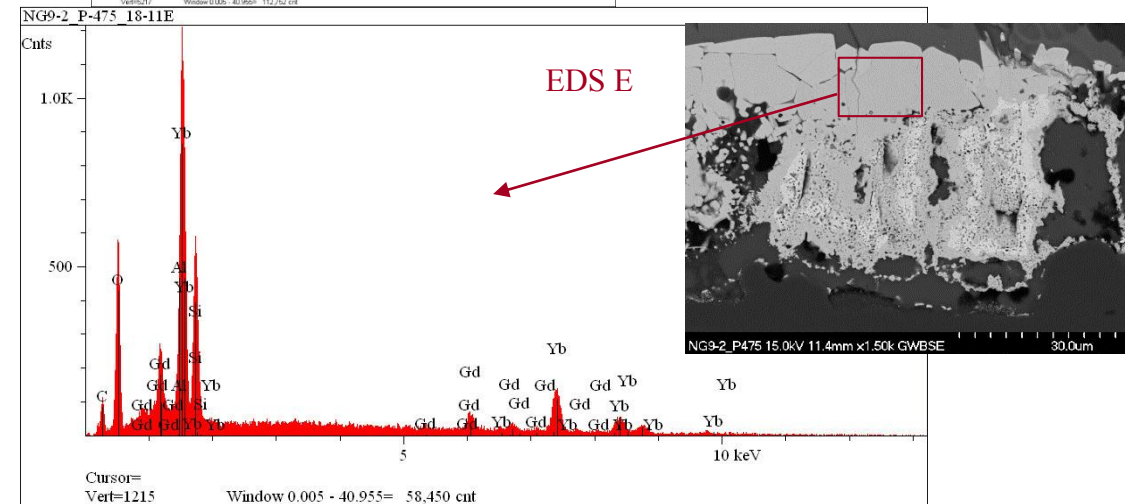
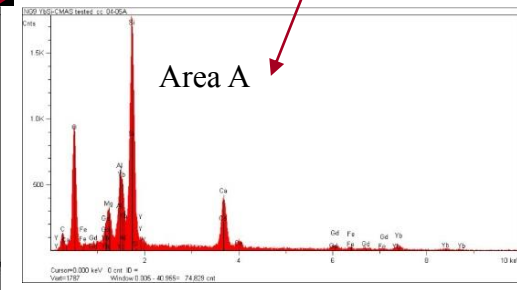
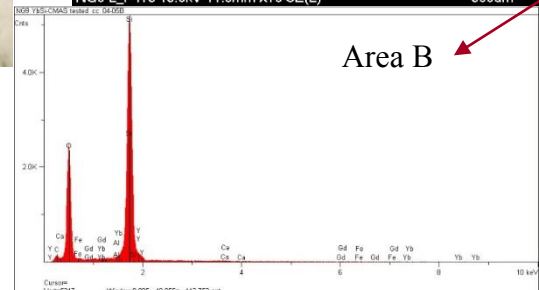


Y₂Si₂O₇ Substrate Exposed to CMAS at 1200°C for 20h

Valerie L. Wiesner



Ahlborg & Zhu



The Advanced EBCs on SiC/SiC CMC Turbine Airfoils Successfully Tested for Rig Durability in NASA High Pressure Burner Rig

- NASA advanced EBC coated turbine vane subcomponents tested in rig simulated engine environments (up to 240 m/s gas velocity, 10 atm), reaching TRL of 5



EBC Coated CVI SiC/SiC vane after 31 hour testing at 2500°F+ coating temperature



EBC Coated Prepreg SiC/SiC vane after 21 hour testing at 2500°F



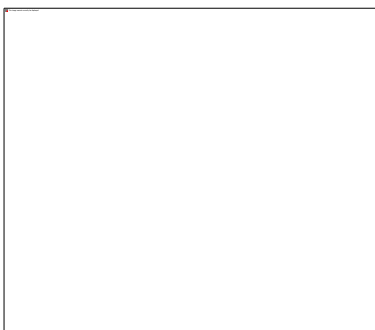
EBC Coated Prepreg SiC/SiC vane tested 75 hour testing at 2650°F



Uncoated vane tested 15 hr

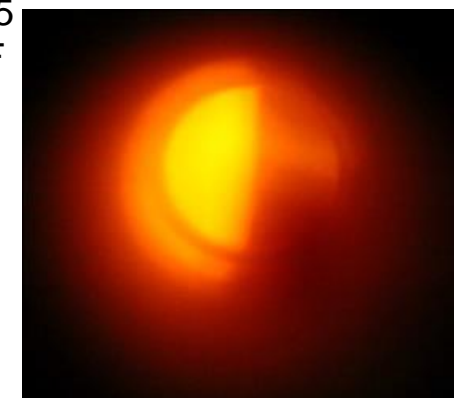


Swirl jet flows



EBC Coated Rig Inner and outer liner testing 2500°F, completed 250 h

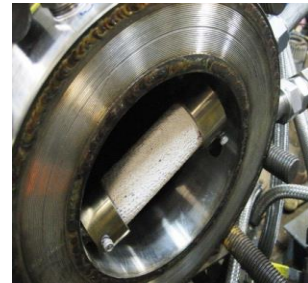
Vane leading edge seen from viewport in High Pressure Burner Rig Testing



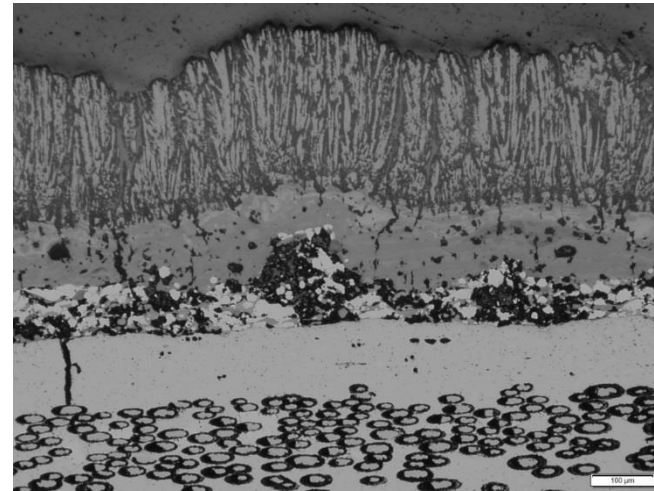
Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs



- Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at T_{EBC} 2700°F, $T_{\text{CMC interface}} \sim 2500^\circ\text{F}$
- The HfO_2 -Si based bond coat showed excellent durability in the long term creep tests



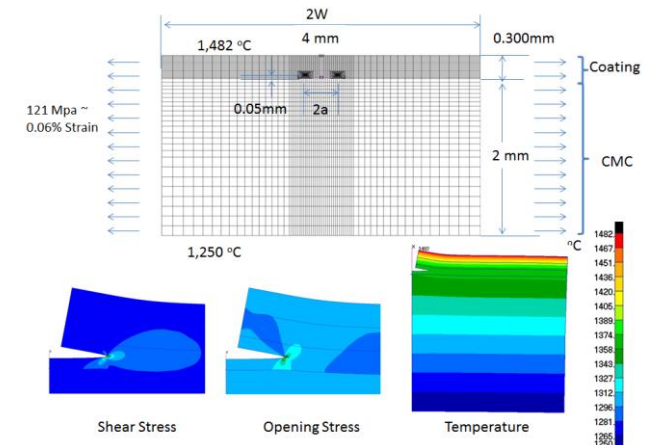
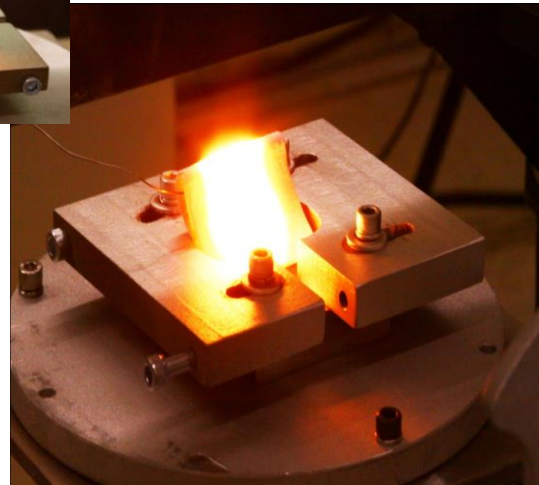
EBC-2.5D CMC
Sub-element demo
in HPBR



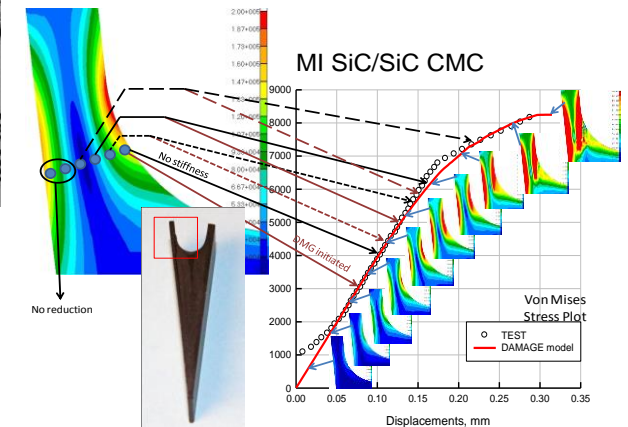
Hybrid EBCs on Gen II CMC after 1000 h low cycle creep fatigue testing



Advanced EBC coated CMC subelement testing and modeling



FEM modeling of EBC-CMC creep and thermal gradient and stress rupture interactions



FEM modeling of EBC-CMC vane trailing edge rig test failure



Summary and Future Directions

- **Durable EBCs are critical to emerging SiC/SiC CMC component technologies**
 - The EBC development built on a solid foundation from past experience, evolved with the current state of the art compositions of higher temperature capabilities and stabilities
 - Multicomponent EBC oxide/silicates with higher stabilities
 - Improved strength and toughness
 - HfO_2 -Si and RE-Si bond coats for realizing prime-reliant 2700°F EBC-designs
 - EBC processing and testing capabilities significantly improved, more advanced compositions designed and realized for complex turbine components
 - Develop rig EBC-CMC subelement simulated tests, helping develop coating property databases and validated life models, aiming at more robust EBC-CMC designs
 - Emphasized turbine airfoil EBC developments, demonstrated component EBC technologies in simulated engine environments of TRL 5, further maturing advanced coating technologies